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THESIS

MODELING THE PERFORMANCE OF THE PT SUR HYDROPHONE ARRAY IN LOCALIZING BLUE WHALES

by

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The Naval Postgraduate School (NPS) Ocean Acoustic Observatory (OAO), which operates a former Sound Surveillance System (SOSUS) at Pt Sur, presents itself as a potentially valuable tool in the detection and localization of Pacific blue whales. By estimating the transmission loss as a function of bearing, range and frequency and synthesizing the ambiguity surface of various model-data linear correlation localization algorithms, an assessment of the array's expected performance for this purpose was obtained. Important findings of this modeling study include estimated maximum detection ranges are longer than 500 kilometers both seaward and along the continental slope due to array beamforming gains and matched field localization algorithms are accurate and robust in the presence of white noise. The application of the results of this study towards the development of a "real-time", large-area blue whale localization and tracking algorithm is promising.

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MODELING THE PERFORMANCE OF THE PT SUR HYDROPHONE ARRAY IN LOCALIZING BLUE WHALES

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ACKNOWLEDGMENTS

It seems that the Northern Right Whale has caused quite a stir by not avoiding the ships transiting their winter grounds. One of a many near extinction, these magnificent animals have expedited the introduction of many seagoing organizations into the unlikely field of whale conservation. It appears that even an aviator has joined the ranks.

I have to recognize a substantial population of people that have assisted me with this thesis. The biology portion included; Dr. Chris Clark, Harold Mills and Russ Charif of Cornell University, Sean Hayes of the University of California at Santa Cruz and Dr. Eugene Haderlie of the Naval Postgraduate School. Surrounded by the most spectacular ecosystem on the planet, Dr. Haderlie reignited my passion for the sea. Additionally, gratitude must be directed towards LT Matt Pickett, a pilot for the NOAA Corps. The four days of flying, which included the sighting of over 25 blue whales, was absolutely a phenomenal experience.

The acoustics portion was fueled foremost by my advisor Dr. Ching-Sang Chiu. His patience in dealing with my perpetual "blank stare" merits a presidential citation. Chris Miller, Rob Bourke and Stephan Hudson, although most certainly celebrating my departure, deserve a wealth of gratitude for helping to tame the computer demons that haunt me still. Dr. Curtis Collins, who actually convinced Dr. Chiu to take me onboard with only six months until graduation, deservingly will receive all financial proceeds from this project.

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I. INTRODUCTION

A. BACKGROUND

The acoustic activity of the blue whale, Balaenoptera musculus, is widely documented yet poorly understood. Although evidence of assumed biological origin low frequency calls has existed since the 1960's (Walker, 1963; Kibblewhite et al., 1967; Northrup et al., 1968), it is not clearly known what causes them to vocalize. Hypotheses for balaenopterid vocalizations range from communication (Payne and Webb, 1971; Watkins, 1981, Watkins et al., 1987), bathymetric echolocation (Clark, 1994; Clark and Ellison, 1993) and echolocation of zooplankton masses (Payne and Webb, 1971; Watkins, 1981). Although extensive documentation of frequency structure and duration exists, a long-term monitoring of where and when the vocalizations are being made must be accomplished to test the validity of these theories.

The Naval Postgraduate School (NPS) Ocean Acoustic Observatory (OAO), which operates a former Sound Surveillance System (SOSUS) at Pt Sur, presents itself as a potentially valuable tool in the detection and localization of Pacific blue whales. Experiments (Clark and Fistrup, 1995; McDonald et al., 1995) have verified that low frequency calls of blue whales can easily be detected in this way. The 1995 experiment, which occurred off of the southern California coast using a combination of SOSUS and additional passive acoustic devices, determined that acoustic detections of blue whales exceeded visual sightings by a ratio of 6:1 (Clark and Fistrup, 1995) .

B. THESIS OBJECTIVES

Several direct recordings of the blue whale vocalization have resulted in an

understanding of their characteristic calls. In Table 1, a summary of these published historical recordings are presented in chronological order. These recordings demonstrate the consistency of the animal's calls and lead to the classification of the "A" and "B" type signals.

The primary objective of this thesis focuses on the feasibility of detecting and localizing each of the primary signals produced by the blue whale; the "A" call, an amplitude modulated signal with a carrier at 90 Hz, the "B" call, a frequency modulated signal centered at 17 Hz and a 51 Hz tonal embedded in the "B" call. Each of the 90, 17 and 51 Hz signals and their respective propagation in a model Central Pacific ocean are synthesized as if the whale were vocalizing at a distance from the Pt. Sur hydrophone array. As these signals propagate through the medium, they are modified and arrive at the receiver with a multi-path structure. This complex multi-path structure, unique to the range and depth of the source, forms the basis for achieving localization through matching model predictions to data.

Two areas of the array performance are assessed. The first involves an investigation into the detection ranges along both the "open" water and "along continental slope" radials from the array's location. The second area deals with the accuracy and robustness of linear, matched field processing schemes in localizing blue whale vocalizations.

C. OUTLINE

The remainder of this thesis consists of three chapters. Chapter II contains a description of the approach. It describes the propagation model used to calculate

Beamish and Mitchell (1971) Atlantic

25 kHz	theorized as zooplankton echolocation
59.2 +/- 1 dB	source level
	vocalized while feeding, 5000 clicks heard

Cummings and Thompson (1971b) Atlantic

20, 25, 31.5 Hz	strongest components in the 1/3 octave band
50, 63 Hz	secondary components in the 1/3 octave band
390 Hz	one second pulse
188 dB	source level
	3 part sequence lasting 36.5 sec no behavior correlation 6-169 m depth

Cummings and Thompson (1994)

17.5 Hz	six spectral lines about 1.5 Hz apart lowest at 17.5 (1st part)
19, 18, 17 Hz	call begins at 19 ,sweeps down in freq to 18 in first 3-4 secs then held until last 5 sec, then down to 17 Hz (2nd part)
	19 sec duration of two part vocalization

Clark and Fristrup (1995) Pacific and Atlantic

50, 90 , 17.5 Hz	IUSS recorded Eastern Pacific Blue
17.5 Hz	IUSS recorded Western Atlantic Blue

Thompson, Findley, Vidaland and Cummings (1996) Pacific

17.8 Hz	harmonically rich FM tone fundamental designated **"B type"** call
53.4 Hz	strongest component (third harmonic of "B" call) drops to 51 Hz in the last 2 sec with median duration of 14.8 sec
90 Hz	AM tone demonstrating this band of energy as a fifth harmonic designated **"A type"** call of median duration 12.2 sec (fundamental frequency of 18 Hz)
98-25 Hz	short duration (1 sec) downward sweep with median frequency modulation at 52.5 Hz

Table 1. Summary of pertinent blue whale vocalizations.

transmission loss and synthesize multi-path arrival structure. It also discusses the databases utilized in creating a Central Pacific Ocean model. The assessment of the detection ranges and localization performance uses these models. Chapter II also describes three linear processing schemes whose performance in localizing the blue whale calls is the thrust of this investigation. Chapter III provides a discussion of the modeling results pertaining to detection range and localization performance. Chapter IV presents the conclusions and recommendations.

II. METHODOLOGY

A. DETECTION RANGE ESTIMATION

1. Environmental Model

The DBDB-5 bathymetric data provided by the Naval Oceanographic Office (NAVOCEANO) was utilized to provide an extensive domain for possible long range acoustic propagation of low frequency sounds. The bathymetry enclosed in a circle with a 700 km radius, centered at the array, was utilized. The database has a resolution of 5/60 of a degree in both latitude and longitude.

The array itself is situated on the down-slope of a submerged topographical feature known as the Sur Ridge. The depth of the array is approximately 1340 meters. A sector of 210 to 310 degrees true appears to be a long range, obstruction free view of the Pacific Basin. The Pioneer and Guide Seamounts exist to the north while the Davidson Seamount provides a small obstruction to the south. A contour plot of the bathymetry in the area of interest is illustrated in Figure 1. The bathymetry data for both an "open" water and "along continental slope" transect are displayed in Figure 2.

The sound speed profile (SSP) in the ocean model was derived from a 14-station CTD survey conducted by Collins et al. (1997) on board the *Research Vessel Pt Sur* in July of 1996. The stations were taken along a transect between Sur Ridge and the Pioneer Seamount. To establish a nominal profile for acoustic modeling, the SSPs were averaged together and passed through a canned cubic spline smoothing program in MATLAB to remove any large gradients due to fine structure which could result in numerical instability when tracing acoustic rays. The resultant profile is shown in

Figure 2.

A MATLAB program called *ray3d* (Chiu et al., 1994) was used to perform eigenray searches and compute signal amplitudes. Additionally, the program calculates travel times and phase shifts along the ray paths and generates multi-path arrival structure. The program requires root-mean-square (RMS) wave height, sediment density and sediment sound speed as inputs.

Pertinent documentation of the sediment was found in "Initial Reports of the Deep Sea Drilling Project, Vol. 18, site number 173". This publication documents the findings of the sediment characteristics found in 3000 m of water at approximately 100 km offshore of Cape Mendocino. The upper 140 m of sediment yields an approximate sound speed of 1600 m/s and a density of 1700 grams per cubic centimeter. From 140 m to 320 m, the sediment exhibits just a slightly increased density and sound speed. At 320 m below the sea floor, a thick basaltic layer is encountered.

Sea surface roughness data was obtained from the climatological database of the Naval Pacific Meteorology and Oceanography Center (NAVPACMETOCCEN). A value of 1.84 m (6.025 ft) was calculated as a mean wave height for the entire year with a standard deviation of 0.129 m (0.424 ft). In order to input this information into *ray3d,* the annual mean wave height was converted to RMS wave height.

2. Acoustic Propagation Model

As a whale vocalizes at a distance from the array, the sound arrives at the receiver via a multitude of possible ray paths. The Hamiltonian Acoustic Ray-Tracing Program for the Ocean (HARPO) was used to calculate these ray paths. By numerical integration

of the Hamilton's Equations, this program traces the paths of acoustic rays as they travel through an analytic model ocean. The original version of this program (Jones et al., 1986) was upgraded in 1994 (Chiu et al., 1994) to allow for the input of gridded bathymetry and sound speed data. The upgraded program was used in this study.

Invoking acoustic reciprocity, a vertical "fan" of acoustic rays were launched from the Pt Sur array. Rays with initial elevation angles from -3 to 30 degrees were traced. The limits of the launch angles were selected based on the bottom slope at Sur Ridge and the critical angle associated with water-sediment interface. Rays unimpeded by the bottom slope near Sur Ridge, with angles less than critical at the sea floor, or that turn before reaching the bottom were allowed to cycle through the model ocean. As stated earlier, eigenray extraction and arrival structure calculations are accomplished by *ray3d.* Once identified, the eigenray's signal amplitude $\mathbf{b}_n$, phase shift Φ_n and travel time $\mathbf{t}_n$, are computed. A coherent sum of the multi-path contributions then gives the predicted receive signal. Given the complex envelope of the source signal **s(t)**, the complex envelope of the predicted receive signals is

$$r(t) = \sum_{n=1}^{N} s(t-t_n) b_n e^{-i[2\pi f_0 (t-t_n) + \Phi_n]} \qquad (1),$$

where **N** is the number of eigenrays and f_o is the carrier frequency of the source signal.

For a unit amplitude tone transmitted at a frequency of f_o, **s(t)** is constant in time. Therefore, the transmission loss, TL, is

$$TL = -10 \log (r\, r^*) \qquad (2),$$

with

$$r = \sum_{n=1}^{N} b_n e^{-i[2\pi f(t-t_n)+\Phi_n]} \qquad (3)$$

and where the * symbol used in Equation (2) denotes the complex conjugate.

The transmission losses calculated at 17, 51 and 90 Hz, respectively, along both "open" water and "along continental slope" transects are shown in Figure 3. The "open" water radial is oriented on a 230 degree True azimuth from the array, while the "along continental slope" radial was directed towards the Farallon Islands to the north. For each transect, the only appreciable difference between the transmission loss curves at the frequencies of interest is attributed to the frequency dependent effects of surface scattering and bottom interaction.

3. Figure of Merit Estimate

An estimate for omnidirectional noise was obtained from the Tactical Environmental Simulation System (TESS) available at the Naval Postgraduate School. Given the input parameters of time of year and location, TESS provides an output of ambient noise level. A late summer profile revealed an omnidirectional level of 75 dB re 1 $\mu Pa^2/Hz$. The summer profile was chosen due to the arrival of the blue whales to the Monterey area in late summer.

The beamforming capability of the array allows for a reduction of the

omnidirectional noise level. An estimate of the array gain AG is

$$\begin{aligned} \mathbf{AG} &= -10 \log(\text{horizontal beamwidth} / 360 \text{ degrees}) \\ &= -10 \log(10 / 360) = 15.6 \text{ dB} \qquad (4), \end{aligned}$$

where the 10 degree horizontal beamwidth is an average for all the bearings. Application of this array gain number provides a significant 15.6 dB reduction in noise.

In order to estimate the maximum detection ranges along the different radials, it is necessary to establish a figure of merit (FOM) estimate. Therefore, FOM is

$$\begin{aligned} \mathbf{FOM} &= \mathbf{SL} - (\mathbf{AN} + 10 \log \Delta f - \mathbf{AG}) \\ &= 175 - (75 + 10 - 15.6) = 105.6 \text{ dB} \qquad (5), \end{aligned}$$

where **SL** is the source level, Δf is the bandwidth of the signal and **AN** is the omnidirectional ambient noise level. The SL estimate of 175 dB re 1 µPa is a "low end" estimate obtained by the authors referenced in Table 1. Of the three signals utilized for this study, the 90 Hz signal has the largest bandwidth. Estimated at 10 Hz, this bandwidth was chosen to provide the most conservative FOM estimate. By applying the result of (5) to the transmission loss curves, a maximum detection range estimate can be obtained.

B. LOCALIZATION PERFORMANCE SIMULATION

1. Signal Models

An underwater recording made by the Cornell University Lab of Ornithology (Charif, pers comm., 1997) was utilized to simulate the source signals. The data was recorded on the *Research Vessel Cory Chouest* in September 1995 and sampled at 400 Hz. This vocalizing whale was sighted off the coast of southern California at approximately 1 AM local time. A spectrograph of the recording is illustrated in Figure 4. The vocalizations presented in the spectrograph match the frequency structure and duration reported in the existing literature. This further suggests that low frequency blue whale calls are strikingly invariant throughout the Atlantic and Pacific Oceans and from one blue whale to the other.

Two recognizable "calls" from the recording can be identified. The first call, designated the A call, manifests itself as a pulsing amplitude modulated tone of approximately 17.5 second duration centered around 90 Hz. The second, the B call, is present as a frequency modulated down sweep with a 17 to 18.5 Hz fundamental lasting approximately 15 seconds. The third harmonic of this down sweep, centered around 51 Hz, dominates.

In order to synthesize the receive signals using *ray3d*, it is necessary to provide the complex envelopes of the animal's vocalizations. For this reason, signals associated with the 17, 51 and 90 Hz blue whale calls were extracted from the recording and bandpass filtered. A complex demodulation of each of these signals was conducted and resulted in baseband complex envelopes for each. The magnitude of these envelopes are

shown in Figure 5. These near-field signals were taken to be the source signals.

A visual illustration of the synthesis of the received signal at two different source locations is given in Figure 6. Both the relative magnitudes of the arrival structure of the 17 Hz signal and the associated eigenray magnitude-time structures are shown. The distortion of the source signal in the arrival structure is due to the multiple eigenrays that scale and delay the source signal differently, causing interferences when combined. The signal distortion is generally different for different source locations and this is the basis of any model-based localization algorithm.

2. Localization Algorithm and Test Procedure

Since the bearing can be determined by conventional plane wave beamforming using the horizontal array, the major concern is whether or not accurate and robust range and depth estimates of a vocalizing blue whale can be obtained. To address this question, a "virtual" blue whale was placed in the ocean model at a designated range and depth from the array on an open water bearing of 230 degrees True. The transmissions of the 90-Hz A call, the 17-Hz B call and the 51-Hz B-call harmonic were simulated using the source signal and propagation models previously described. The simulated range and depth of the blue whale and the simulated arrival structure at the array were then used to represent the "true location" and "data," respectively, in modeling the localization performance.

The resolution, accuracy and robustness to noise of three different time-domain Bartlett-type localization algorithms (Clay, 1987; Miller and Chiu, 1992; Miller et al., 1996) applying to each of the signals, were studied and contrasted. Each algorithm is

based on a linear correlation between a certain property of the observed signal (i.e., data) and the predicted (i.e., modeled) signal property for a number of possible source locations in a range-depth grid. The collection of the maxima of the normalized correlation functions associated with the different tried locations produces the so-called ambiguity surface (Tolstoy, 1993).

The global maximum of the ambiguity surface is the "best" estimate of the blue whale's range and depth, its horizontal and vertical dimensions define the footprint, and distant peaks of significant heights are potential false targets. Therefore, studying the behavior of this ambiguity surface, in particular, how it changes with a different algorithm, a different signal type and a different signal-to-noise ratio (SNR) in the data, is central to the assessment of localization performance. The difference between the estimate and the controlled true location is a measure of accuracy. The size of the footprint is a measure of resolution. The heights and number of the distant peaks measure ambiguity. While finally, the changes in all of the above measures with controlled decreases of SNR are directly related to robustness.

The first localization algorithm being investigated is a fully-coherent scheme involving cross-correlations between the complex envelopes of the observed and predicted signals (hereafter referred to as "coherent matching"). The remaining two algorithms are incoherent schemes. For the cross-correlations, the second algorithm uses the magnitude of the complex envelope (hereafter referred as "magnitude matching"), whereas the last algorithm employs the square of the signal envelope (hereafter referred as "power matching"). Mathematically, the correlation functions associated with coherent,

magnitude and power matching are, respectively,

$$C_{coherent}(\tau)=\frac{\int_{-\infty}^{\infty} r_D(t)r_M^*(t+\tau)d\tau}{\sqrt{\int_{-\infty}^{\infty} r_D^2(t)dt}\sqrt{\int_{-\infty}^{\infty} r_M^2(t)dt}} \qquad (6),$$

$$C_{magnitude}(\tau)=\frac{\int_{-\infty}^{\infty} |r_D(t)||r_M^*(t+\tau)|d\tau}{\sqrt{\int_{-\infty}^{\infty} r_D^2(t)dt}\sqrt{\int_{-\infty}^{\infty} r_M^2(t)dt}} \qquad (7) \text{ and}$$

$$C_{power}(\tau)=\frac{\int_{-\infty}^{\infty} |r_D(t)|^2|r_M^*(t+\tau)|^2d\tau}{\sqrt{\int_{-\infty}^{\infty} r_D^4(t)dt}\sqrt{\int_{-\infty}^{\infty} r_M^4(t)dt}} \qquad (8),$$

where r_D is the complex envelope of the observed (data) arrival structure and r_M is the complex envelope of the predicted (model) arrival structure.

In the investigation of footprint sizes, a small search grid of 1 km in range (50 - 51 km from the array) by 125 m in depth (25 - 150 m) but with densely spaced grid points was used. The vocalizing whale was positioned at a depth of 115 meters and a range of 50.5 km from the array. The simulation of footprints not only helps to quantify and contrast the resolutions of the different algorithms for different types of calls, but also provides vital information for the design of an optimal search grid for a real application. There is, of course, a trade-off between resolution and computational efficiency. In order

to expedite an investigation of potential distant false targets which might introduce difficulties in obtaining an unambiguous location estimate, coarse spacings of 0.2 km in range and 25 m in depth were used to occupy a large search grid covering ranges from 25 to 75 km and depths from 25 to 150 m. It is fully recognized that this coarse search grid is not adequate for a real application of locating blue whales. However, it is suitable for a quick analysis pertaining to distant false targets.

III. ANALYSIS AND RESULTS

A. DETECTION RANGE

Application of the FOM value calculated in (6) to all the "open" water coherent transmission loss curves yields a range estimate of at least 500 km. The "along continental slope" detection ranges appear bounded only by the coastline. As would be expected, the 17 Hz signal appears to experience the least transmission loss along the "open" water transect, yet all three of the signals appear to trend equally with distance from the array. A critical FOM value of approximately 85 dB, representing a threshold for detection of the blue whale calls in ranges greater than 200 km, can be visualized in Figure 4.

The source level contributes to the variability of this critical FOM value. A "conservative value" of 175 dB re 1 μPa was utilized in estimating the ranges. Similar calls recorded by the *Research Vessel Cory Chouest* in 1994 (one year prior to the recording used in this thesis) established a source level of 184 dB re 1 μPa (Charif, pers comm., 1997). This source level estimate is just four decibels short of a 1971 estimate of 188 dB re 1 μPa (Cummings et al., 1971). Any increase in the source level from 175 dB re 1 μPa would further extend these already long detection ranges.

B. LOCALIZATION PERFORMANCE

1. Footprint

As stated earlier, the size of the footprint for each of the three signals provides a measurement of resolution. As the footprint increases in size, both ability to resolve multiple whales vocalizing at the same time and the required minimum grid spacing

increase. The approximate dimensions, in meters, of the footprints are listed in Table 2.

Frequency (Hz)	Horizontal (m)	Vertical (m)
17	300	60
51	150	20
90	50	5

Table 2. Horizontal and vertical dimensions of the footprints for each signal

The 17 Hz portion of the B call exhibits the largest acoustic footprint of the three signals studied. The footprint size, however, decreases rapidly as frequency increases. The optimal spacing for the localization grid for real applications should be half the size of the smallest footprint (i.e., 25 m in range and 2.5 m in depth). This dimension approaches the actual length of the animal and could provide the resolution needed to distinguish between whales vocalizing simultaneously at a distance of one grid spacing apart.

2. False Targets

The presence of high distant peaks in a localization grid is indicative of "false targets" and is directly related to the ability of an algorithm to localize unambiguously. The goal, of course, is to select an algorithm that exhibits the highest contrast between the distant peaks and the peak at the true location in the ambiguity surface. The ambiguity surfaces calculated over a large area for each of the three matching algorithms are shown in Figures 10-12. Although the magnitude matching scheme for the 17 Hz signal lacks the side lobes that are present in the coherent and power matching (see Figure 10) at 43

and 60 km of range, the overall results, including the considerations of both the 51 and 90 Hz ambiguity surfaces (see Figures 11 and 12), illustrate that the best choice for an unambiguous estimate would be the coherent matching algorithm.

3. Effects of White Noise

When gaussian white noise is introduced into the signal to systematically change the signal to noise ratio (SNR), the degradation of localization performance due to random fluctuations can be evaluated. Two quotient measures were used to quantify the degradation as SNR increases. The first quotient was the actual peak divided by the largest side lobe peak. The second quotient was the actual peak divided by the mean of the top ten side lobe peaks. It is important to note that side lobe peaks existed outside of the dimensions of the respective signal footprint. Figures 13 and 14 illustrate the computed degradation curves for the 17 and 51 Hz signals as a function of SNR. The curves for the 90 Hz signal curves are nearly identical to the 51 Hz curves and thus they are not shown. Using these curves, localization thresholds can be established.

A localization threshold can be defined as the SNR beyond which the two quotients remain larger than unity. Logically, if the maxima of the normalized model-data correlation functions associated with the false targets exceeded the maximum at the actual position of the vocalizing whale , the ratio or quotient would be less than one. In view of Figure 13, the localization of the 17 Hz signal does appear to be sensitive to white noise and requires at least 2 dB SNR, depending on the algorithm used, to ensure localization. As SNR increases past this critical value, all three algorithms appear to be quite robust for the 17 Hz signal.

Figure 14 shows the degradation curves for the 51 Hz signal. For this signal, all three algorithms appear quite SNR independent and strongly robust. Almost all quotient values remain greater to one from 0 to 20 dB SNR. Considering the computed degradation curves shown in Figures 13 and 14, the coherent matching scheme appears to be the most robust in noise-present environment.

IV. CONCLUSIONS

This thesis has attempted to model the performance of the Pt Sur hydrophone array in localizing blue whales. It is important to note that this study provides only a "first order" estimate of the array's ability to provide an accurate estimate of a whale's position. Based upon the results, however, the potential for actual localization using the array appears promising. Detection ranges along "open" water transects were estimated to be greater than 500 km and bounded only by the coastline for "along continental slope" transects. Among the three model-data correlation algorithms assessed, the coherent matching was found to provide the highest resolution and the most unambiguous position estimate. Additionally, the coherent matching scheme was found to provide the highest degree of robustness in the presence of white noise for each of the three signals.

The range-depth localization grid used in this performance study were oriented along a 230 degree True azimuth from the array in order to investigate possible long range Pacific basin localization. The late summer arrival of the blue whales into the Monterey area, however, often brings the animals close to shore. The whales frequent the 200 - 500 fathom isobaths as they feed upon the krill patches that bloom in the nutrient rich upwelled water. The array's orientation may or may not prohibit localization as these animals linger over the continental slope south of the Farallon Islands or venture into the Monterey submarine Canyon. The array's performance in localizing in these near shore regions has yet to be investigated.

The obvious next step would be to test the localization algorithms with actual blue whale calls detected by the array. A large area localization grid utilizing a horizontal

spacing of 25 m and 2.5 m in depth, as determined by the footprint study, is required. A number of factors can pose additional challenges to this task. They include; signal mismatches, multiple animal vocalizations and near shore transmission of the signal. The latter of these topics is beyond the scope of this study.

Signal mismatching can easily occur due to the variability, though small, of the animal's vocalization. Although the "calls" appear standard in the Eastern Pacific region, documentation of acoustic variability is not as well documented as pigmentation variability, which serves as a visual identification of individuals (Calambokodis and Barlow, 1995). Localizing multiple animals that are vocalizing within a group presents yet another challenge. Luckily, of the balaenopterids that do vocalize, the blue whale is more apt to be found alone or in groups of 1- 4. (Calambokodis and Barlow, 1995) As stated earlier, dedicated cataloging of individual vocalizations may greatly assist in this challenge. Further study into each of these topics is needed.

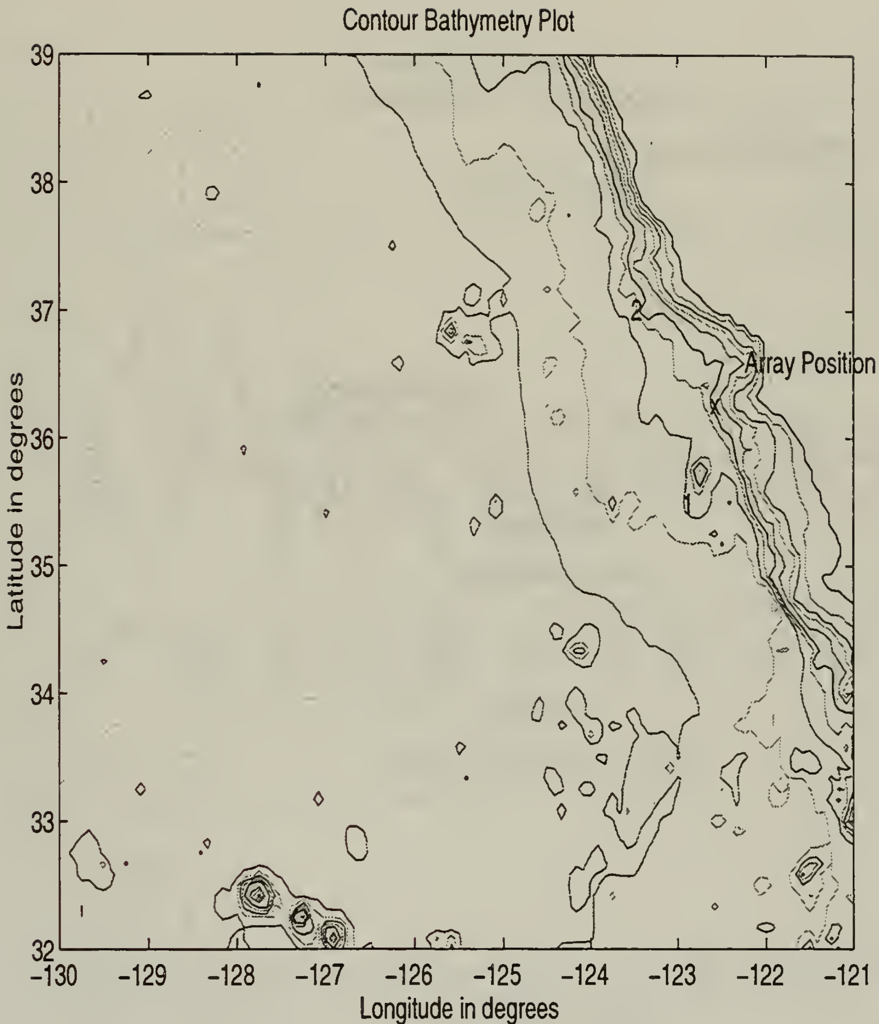

Figure 1. Bathymetry for the Central Eastern Pacific. The "x" indicates the location of the hydrophone array. The Davidson Sea mount is located at position 1, while the Pioneer and Guide Sea mounts are located at position 2. Contour interval is approximately 350 meters.

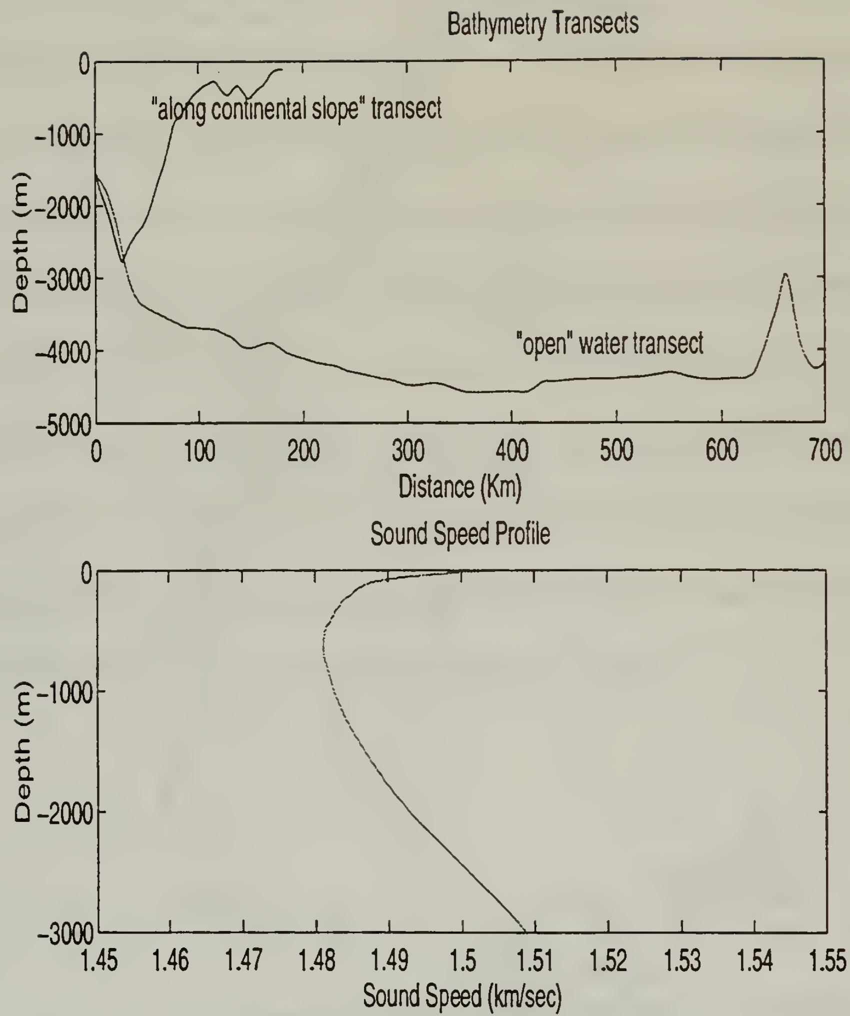

Figure 2. Sound speed profile and bathymetry along two different radials. The top panel illustrates both the "along continental slope" transect, which is oriented towards the Farallon Islands, and the "open" water transect, which is oriented 230 degrees True. Both transects originate from the array's position. The bottom panel illustrates a nominal sound speed profile.

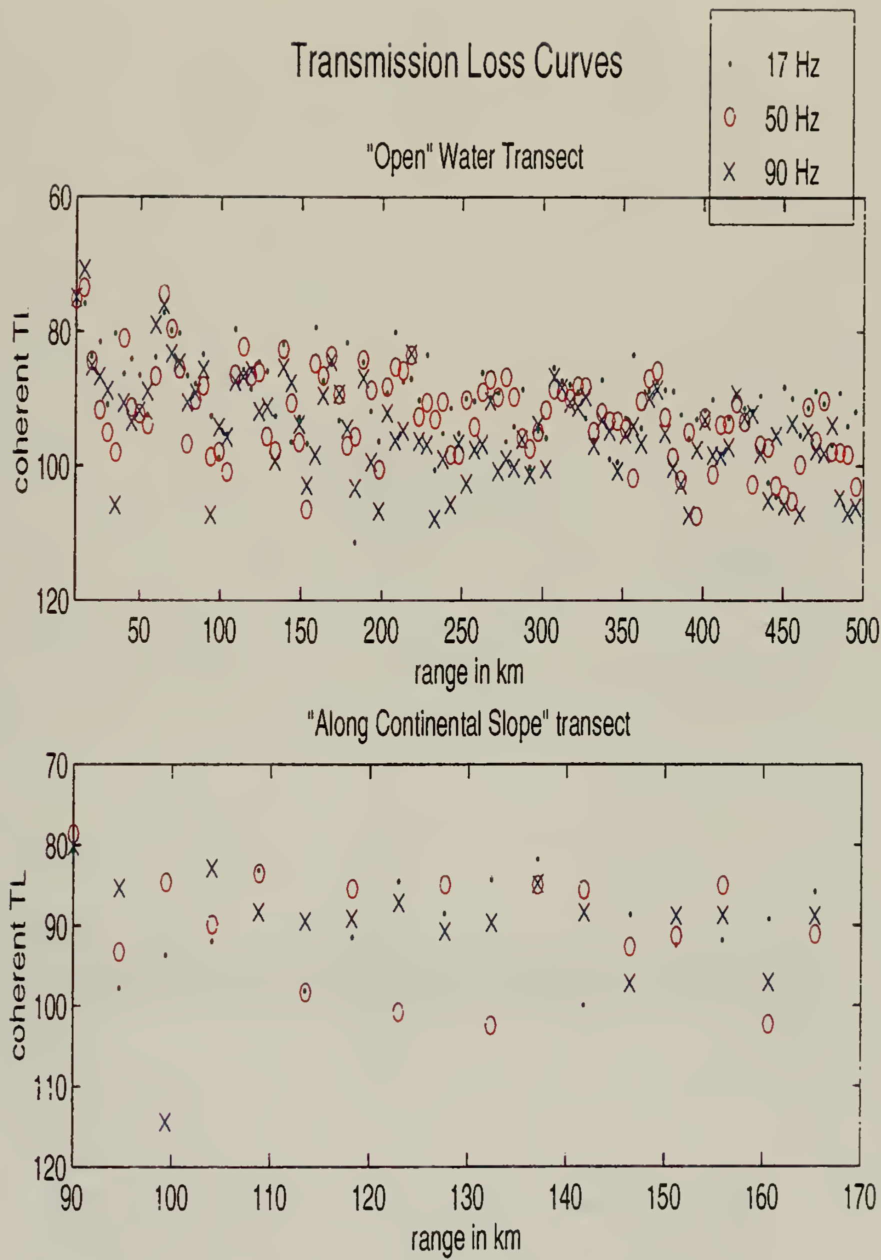

Figure 3. Transmission loss curves for both the "open" water (230 degrees True from the array) and the "along continental slope" (towards the Farallon Islands) transects.

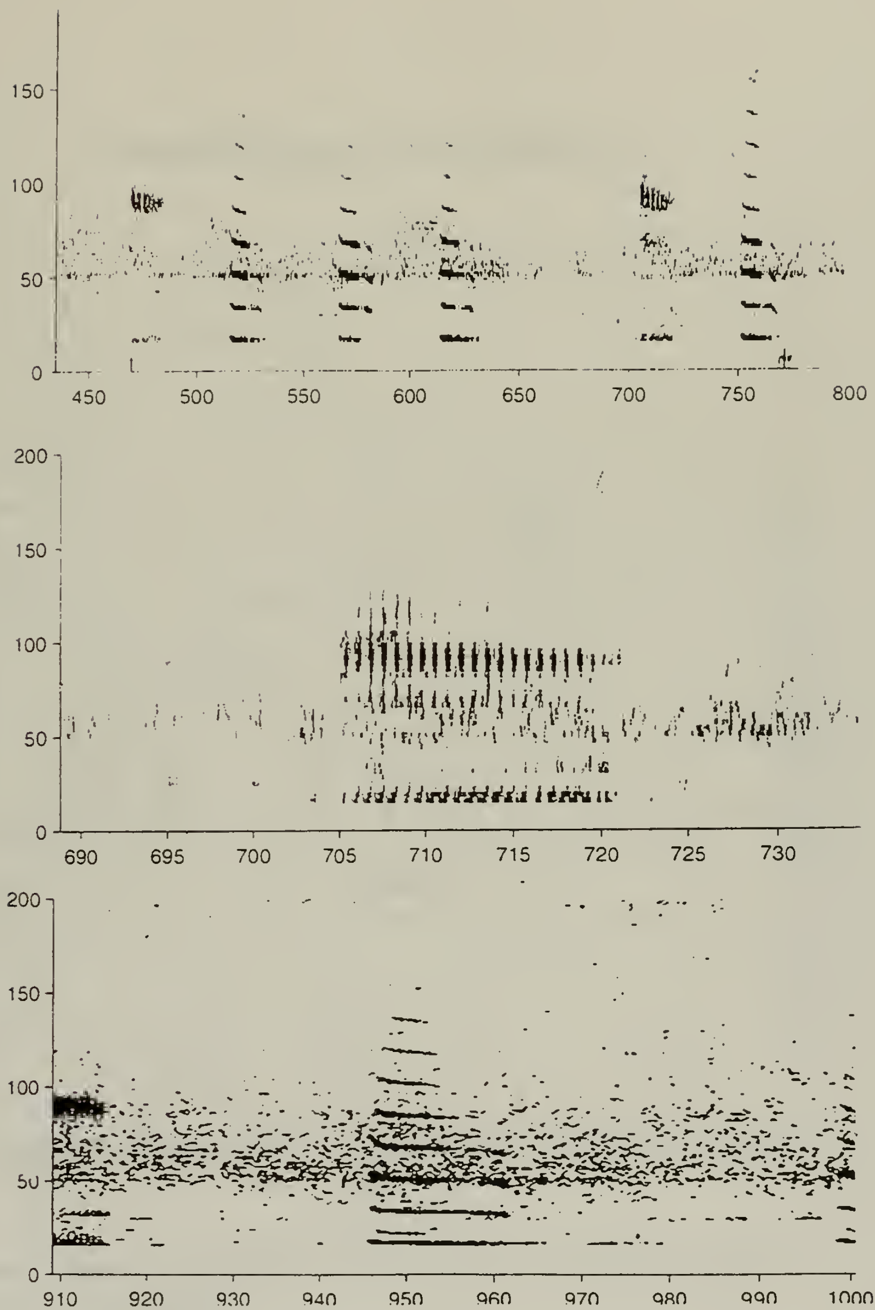

Figure 4. Lofar spectrogram of blue whale vocalizations. The top spectrogram is an A-B-B-B-A-B sequence. The middle spectrogram shows the pulsing structure of the A call which lasts approximately 17.5 seconds. The bottom spectrogram demonstrates the downsweep of the B call, harmonically rich in this example, which lasts approximately 15 seconds. The vertical axis is frequency while the horizontal axis is time index, in seconds, from the beginning of the recording (modified from Charif, 1997).

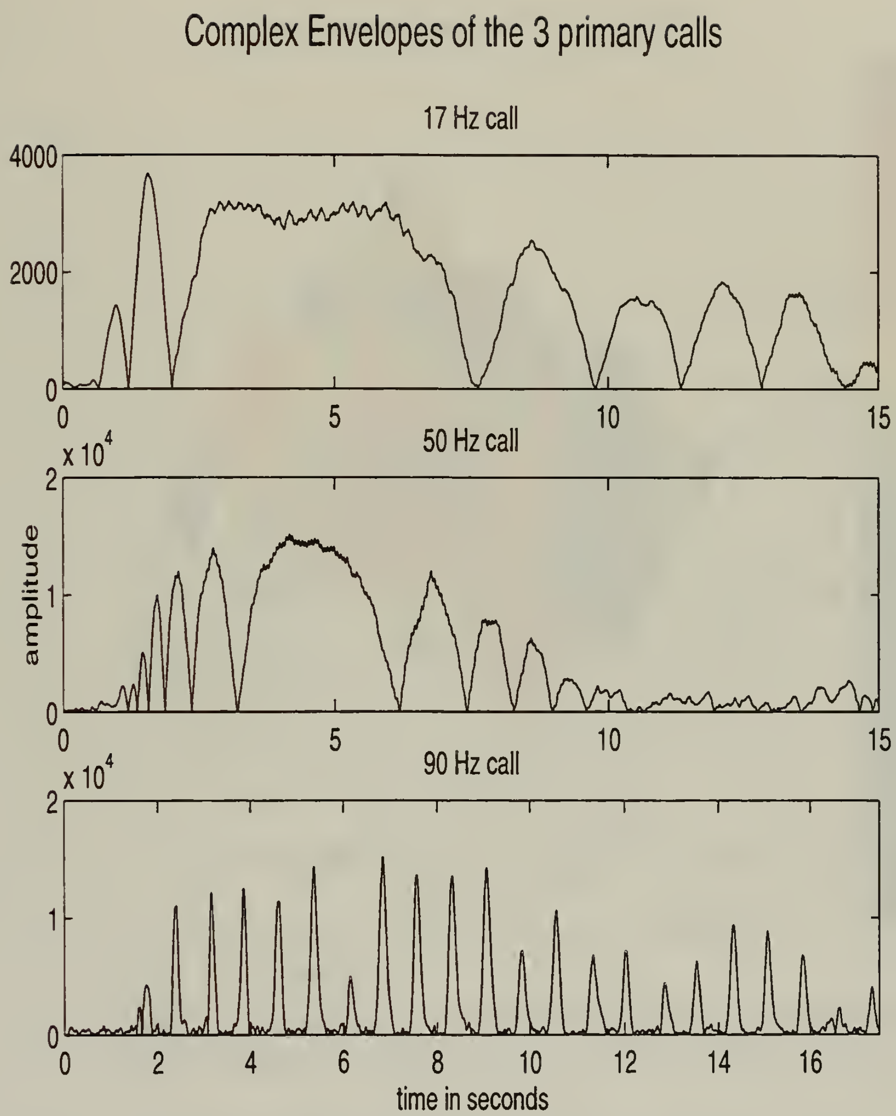

Figure 5. Relative magnitude of the complex envelopes of each of the three source signals.

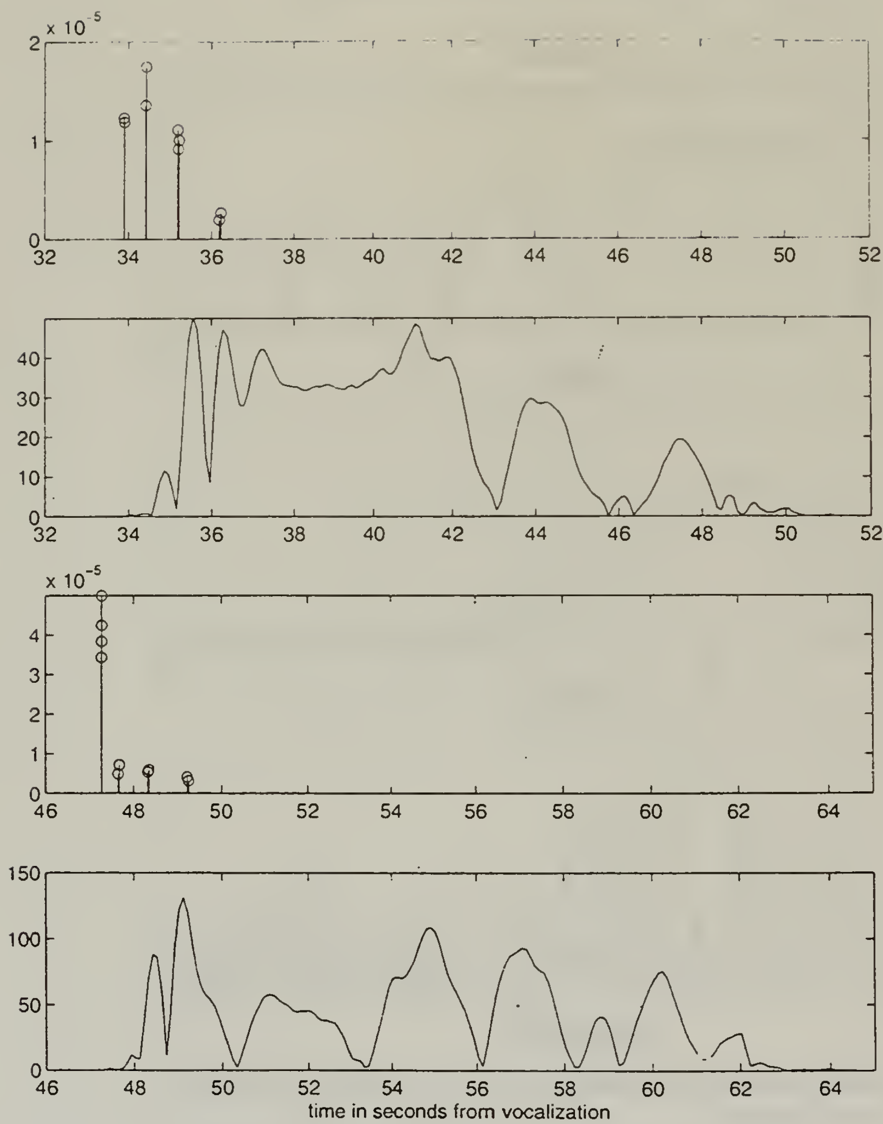

Figure 6. Simulated eigenray magnitude-time structure and the envelope of the associated arrival pattern for the 17 Hz signal for two different whale locations. The top two panels are for a source location of 50 km in range and 120 m in depth. The bottom two panels are for a source location of 70 km in range and 120 m in depth. All ranges and depths are from the hydrophone array.

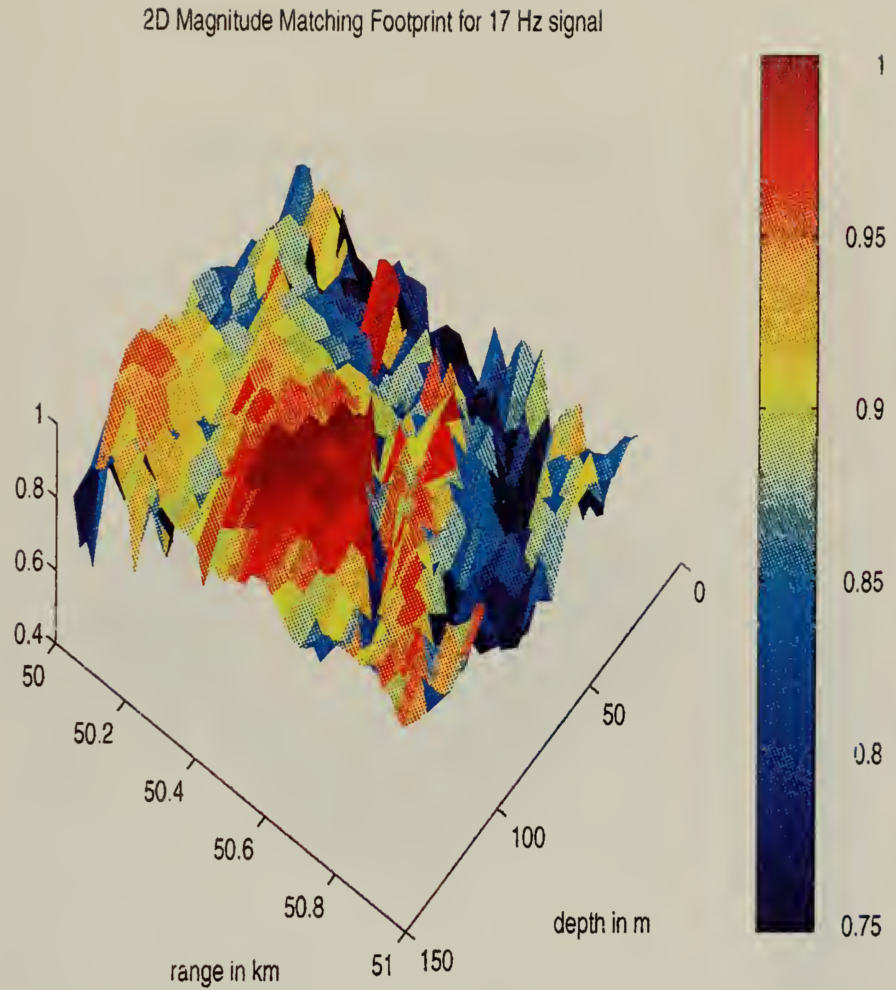

Figure 7. Surface elevation plot of the ambiguity surface produced by the magnitude matching scheme for the 17 Hz signal.

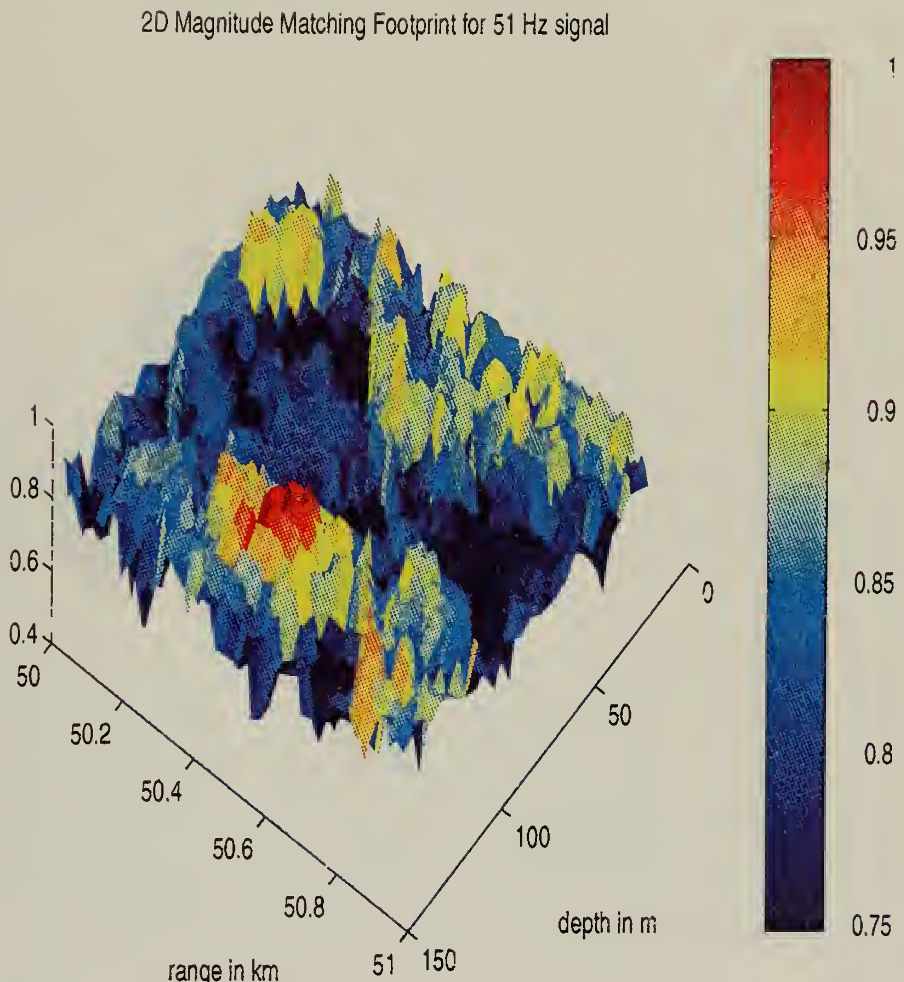

Figure 8. Surface elevation plot of the ambiguity surface produced by the magnitude matching scheme for the 51 Hz signal.

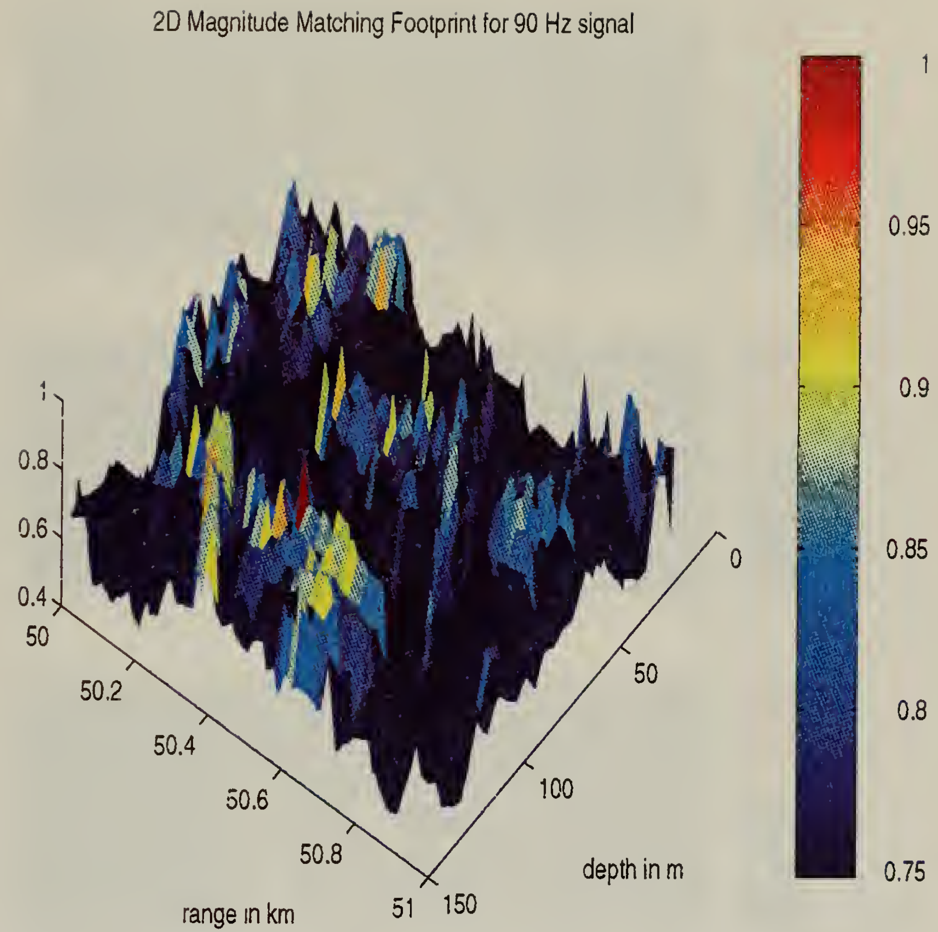

Figure 9. Surface elevation plot of the ambiguity surface produced by the magnitude matching scheme for the 17 Hz signal.

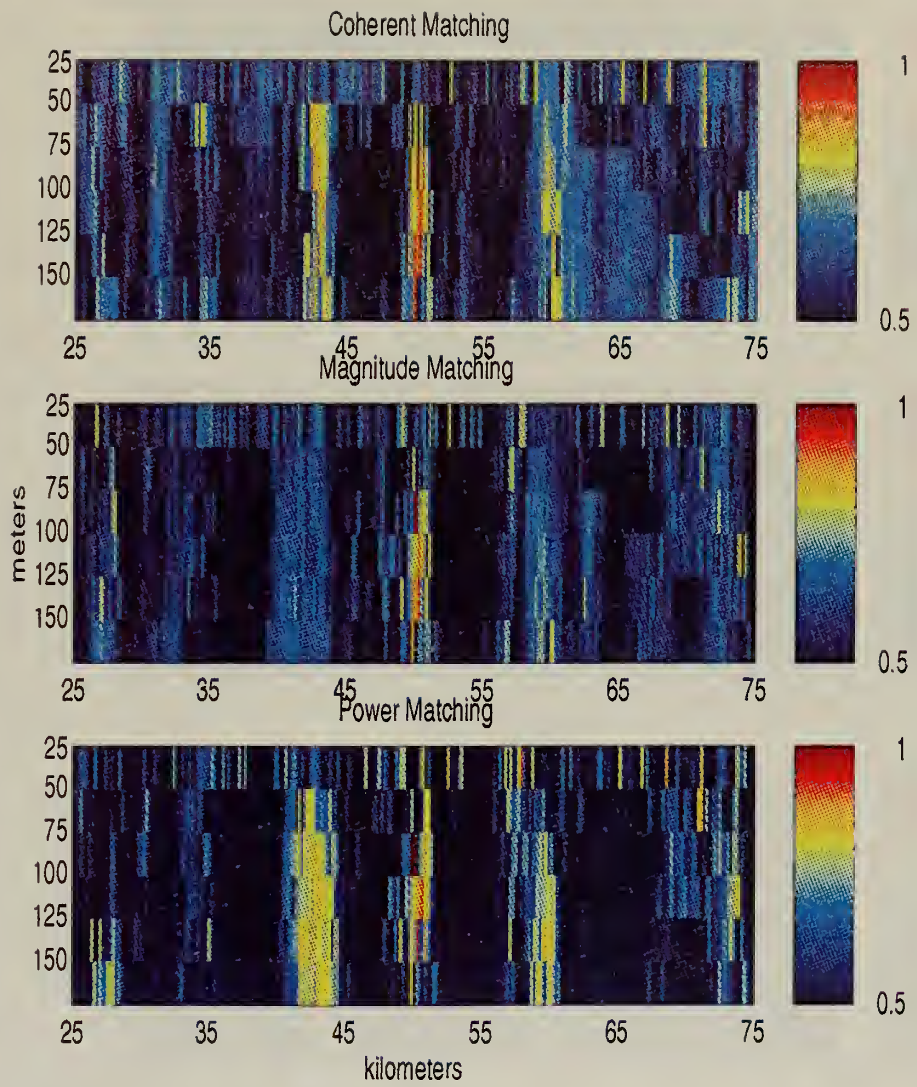

Figure 10. Large-area ambiguity surface for the 17 Hz signal. The source is located at a range of 50 km and depth of 75 m.

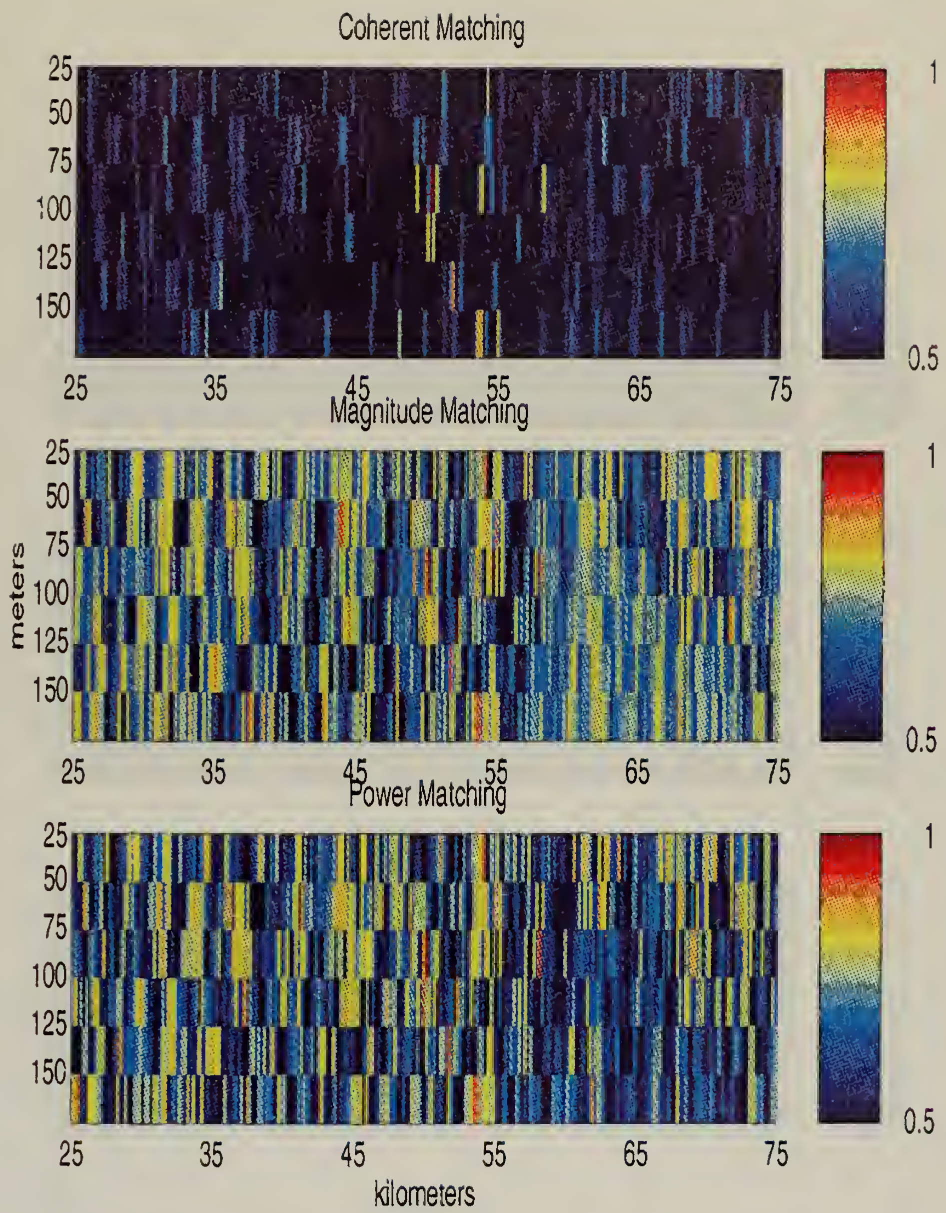

Figure 11. Large-area ambiguity surface for the 51 Hz signal. The source is located at a range of 50 km and a depth of 75 m.

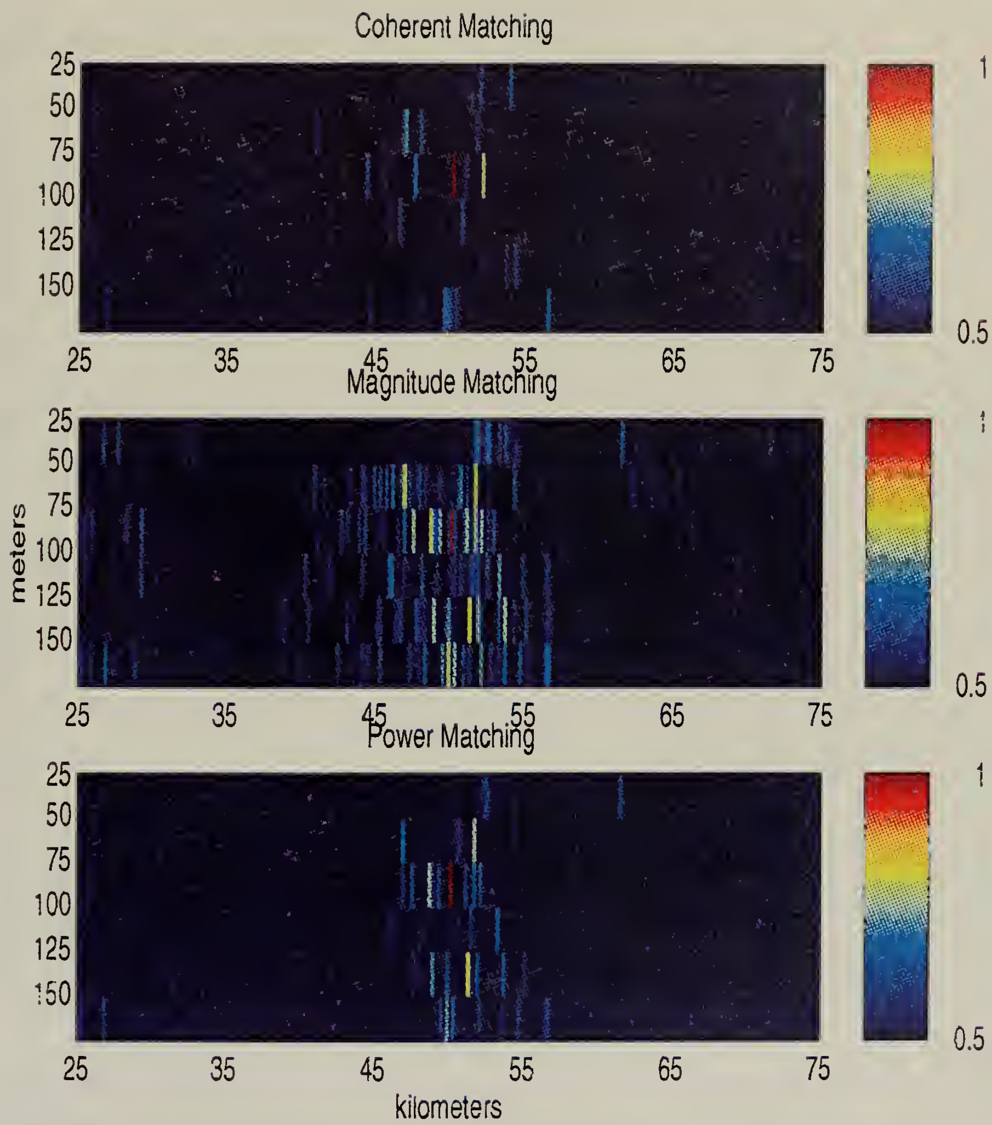

Figure 12. Large-area ambiguity surface for the 90 Hz signal. The source is located at a range of 50 km and a depth of 75 m.

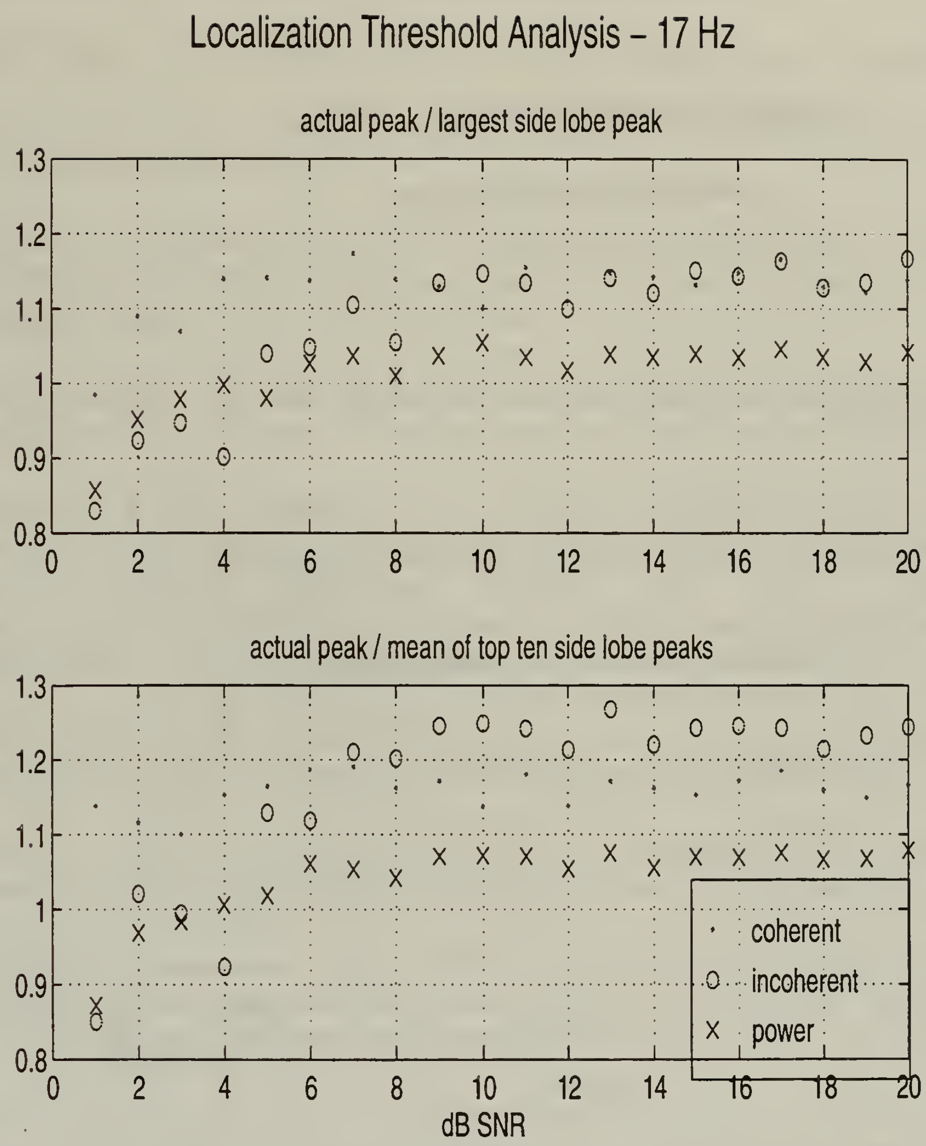

Figure 13. Localization degradation as a function of SNR for the 17 Hz signal. Two quotients are used to quantify the effect of added noise to each algorithm.

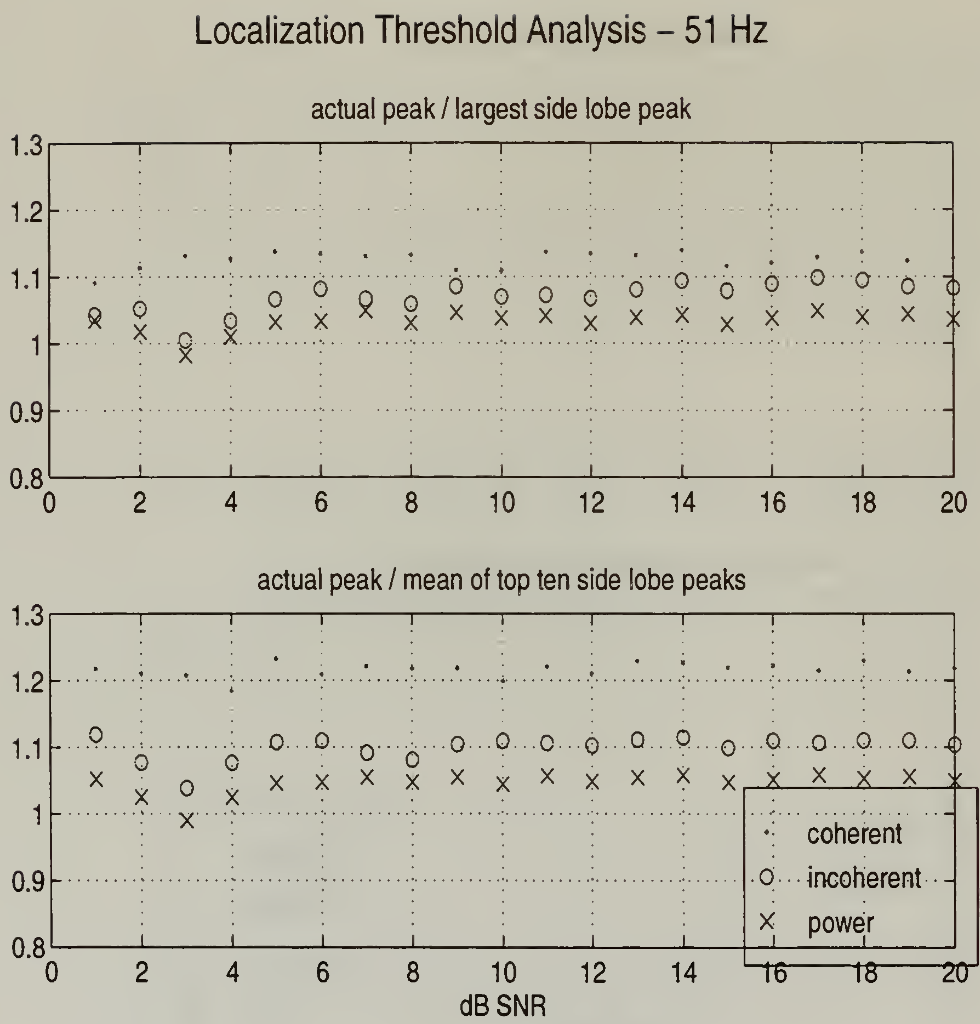

Figure 14. Localization degradation as a function of SNR for the 51 Hz signal. Two quotients are used to quantify the effect of added noise to each algorithm.

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